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SOLAR PHYSICS

Optimal Prediction of the Peak of the Next 11-Year Activity Cycle and of the Peaks of Several Succeeding Cycles on the Basis of Long-Term Variations in the Solar Radius or Solar Constant

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Abstract—We propose a new technique for the optimal prediction of the peak of the next 11-year activity cycle prior to the cycle beginning and of the peaks of several succeeding cycles on the basis of long-term variations in the solar radius or solar constant. The method is based on the already established fact that the long-term cyclic variations of the activity, radius, and solar constant are correlated in both phase and amplitude, since they are caused by some common processes in the Sun. The peak of the succeeding cycle 24 is expected to have the height $W_{max} = 70$ 10 (in units of relative sunspot number). The subsequent cycles 25 and 26, which will be formed during the descent of the current secular cycle, will have still lower peaks with the heights $W_{max} = 50$ 15 and $W_{max} = 35$ 20.

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The optimal medium-term prediction of solar activity variations is possible only for the current 11-year cycle. To this end, some common properties and statistical parameters of the previous 11-year cycles, which were reliably studied, should be analyzed (there were 14 such cycles, namely, cycles 10–23). Although their number is very small, the further development of the current cycle can be extrapolated after its first 18–24 months elapsed and after its curve fell on the curve of one of the known cycle families with high, medium, or low activity levels. As a result, the height and position of the cycle peak as well as the tentative duration of the current cycle can be predicted quite reliably [5].

The predictions of the maximum activity level and of other main parameters of the next 11-year cycle (which has not started yet) have no solid physical background and are sometimes based on incorrect assumptions, since they rely on scarce statistical data. The common properties of cycle families and the regularities in the variations of their maximum activity levels have not reliably been determined yet. There is no adequate physical model describing the secular variations of the solar activity. This hinders any reliable long-term prediction of the maximum activity level of the next 11-year cycle prior to its beginning and the maximum activity levels of the succeeding cycles.

In our previous studies, we concluded that the global secular cycle is a primary (parent) cycle which governs the development of the 11-year (filial) cycles of solar activity, integral radiation flux (the so-called solar constant), and radius [1–3]. We found, in particular, that the duration of 11-year cycles depends on secular cycle phase and generally grows from the rising stage to the maximum and descending stages of the secular cycle [3]. The following universal regularity was revealed: the long-term cyclic variations of the activity, radius, and solar constant are caused by some common processes which occur deep in the Sun and are correlated in both phase and amplitude [1, 2]. The long-term cyclic variations of the solar constant are determined almost entirely by the oscillations of the radius of the radiating photosphere surface. The cyclic oscillations of the activity level, which develop along with the oscillations of the radius (and, therefore, of the solar constant), correlate with the cyclic oscillations of the whole Sun. Therefore, the Sun is not in the state of mechanical and energy equilibrium, and its global spatial and physical parameters exhibit cyclic changes. So, the Sun is a variable star with the correlated 11-year and secular variations of activity, radius, and radiation flux.

Thus, the aggregate long-term high-accuracy data about the secular and 11-year components of cyclic variations in the radius or solar constant provide us with an optimal physically justified indicator of the be-

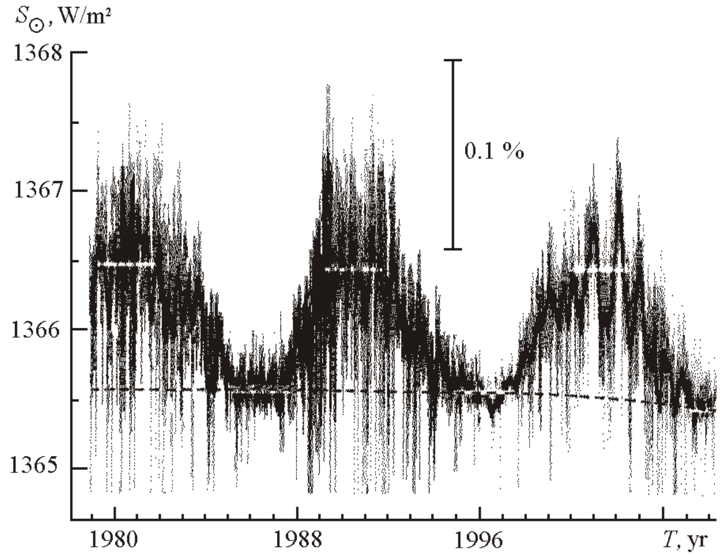

Fig. 1. Variations of the integral solar radiation flux over the period from 1978 to 2006 (the data were taken from www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant): (solid curve) 11-year variations, (dashed curve) secular variations. Individual upward and downward outliers are due to the passage of plages or sunspots over the solar disk.

havior of these variations in the course of several successive 11-year cycles. These data can also be used to predict more accurately the heights of the peaks of these successive cycles. Note that the temporal variations of the solar radius are measured from a circumterrestrial orbit much more accurately than the variations of the integral solar radiation flux [4].

The purpose of this study is to examine the reliable high-accuracy data on the long-term cyclic variations of the solar radius or solar constant in order to develop a new physically justified technique for the optimal prediction of the maximum activity level of the next 11-year cycle and the maximum activity levels of several subsequent cycles (although the predictions for these more distant cycles are less accurate).

Unfortunately we still lack long-term and high-accurate measurements of the solar radius from space. On the other hand, the solar constant $S_{\odot}$ has been measured almost continuously by several space apparatuses since 1978 (solid curve in Fig. 1). The variations of the solar constant also carry information about the corresponding correlated variations of the solar radius [1, 2]. The amplitude of the smoothed cyclic variations of the solar constant is no more than 7 $10^{-4}S_{\odot}$ per cycle, and it rapidly drops. The short-term variations of the solar constant with a typical period of several days (Fig. 1) are due to the passage of plages (upward outliers with the amplitude $+0.001S_{\odot}$) or sunspots (downward outliers with the amplitude $-0.002S_{\odot}$) over the solar disk. Thus, sunspots and plages produce noise in the variations of the solar constant all over the cycle length, especially during the cycle maximum. This hinders the optimal data smoothing and complicates the accurate determination of the parameters of short-term and long-term variations in the solar constant. Nevertheless, the general behavior of the solar constant can still be recognized (solid curve in Fig. 1). Since we have no reliable high-accurate data on the long-term variations of the solar radius, we can only use the existing series of the correlated oscillations of the solar constant.

The integral solar radiation flux in the cycle minimum also drops rapidly from cycle 21 to cycles 22 and 23 (dashed curve in Fig. 1). The same correlated decrease is also observed in the secular solar activity variations (thick curve in Fig. 2). These data were used earlier to prove the existence of the secular component in the variations of the solar constant [1]. The simultaneous rapid decrease of the secular components of the solar constant and solar activity indicate the beginning of the descending phase in the secular cycle. The fact that the secular cycle determines the regularities in the development of the filial 11-year cycles [1–3] can be used for the optimal forecast of the corresponding variations in the main parameters of the next 11-year cycle. In particular, the height of the cycle activity peak and the amplitude of the solar constant variations can be predicted.

The difference between the solar constants in the post-maximum minima of two successive cycles 21 and 22 was –0.02 W/m^2, and the activity W_{max} decreased by 6.4 in cycle 22. The corresponding difference of the solar constants for cycles 22 and 23 was –0.12 W/m^2, and the activity W_{max} decreased by 37.4 in cycle 23. The expected difference between the solar constants in the minima of cycles 23 and 24 is estimated at –0.18 W/m^2. Hence the activity W_{max} can be expected to decrease by 54.0 in cycle 24. Thus, the most likely height of the cycle 24 peak is $W_{max} = 70 \quad 10$. Note that in our study [3] we analyzed the duration of 11-year cycles as a function of secular cycle phase and predicted that cycle 24 would begin in August 2007 (0.4 yr) and that its maximum would come in July 2011 (0.4 yr).

The long-term cyclic variations of the solar radius ($R_{\odot}$) can be calculated from the corresponding variations of the solar constant ($S_{\odot}$) [1, 2]:

$$R_{\odot} = R_{\odot} \quad S_{\odot}/2S_{\odot} = 3.4813 \quad 10^5 \quad S_{\odot}/S_{\odot} \quad \text{[km]}.$$

Long-term variations of the solar constant $S_{\odot}$ and solar radius $R_{\odot}$

Cycle	$S_{\odot}$, W/m^2		$S_{\odot}^{max} - S_{\odot}^{min}$, W/m^2	W_{max}	R_m, km
	maximum	minimum			
21	1366.49 0.06 (December 1979)	1365.57 0.03 (August 1986)		164.5 (December 1979)	0 (August 1986)
22	1366.46 0.06 (July 1989)	1365.55 0.03 (May 1996)	0.89	158.1 (July 1989)	–5.1 (May 1996)
23	1366.41 0.06 (April 2000)	1365.43 0.03 (July 2007)?	0.86	120.7 (April 2000)	–35.7 (July 2007)?
24	1366.24 0.15? (July 2011)?	1365.25 0.10? (September 2018)?	0.81?	70.0 10.0? (July 2011)?	–81.6? (September 2018)?

Note: W_{max} is the maximum relative sunspot number in the given cycle (the corresponding data were smoothed with a 13-month window), $S_{\odot}^{max}$ and $S_{\odot}^{min}$ are the smoothed solar constants measured in the cycle maximum and in the minimum of the cycle's beginning phase.

The table gives the differences between the solar radius calculated for the minima of cycles 22–24 and the solar radius calculated for the cycle 21 minimum. In 2018 the solar radius will be 80 km smaller than it was in the 1990s.

The behavior of the solar constant and solar activity level in several succeeding cycles can be predicted in the same way (but with a smaller accuracy). The 11-year and secular components of the solar constant and activity level will continue to diminish, and the maximum activity level will fall down to W_{max} = 50 15 in cycle 25 and W_{max} = 35 20 in cycle 26 (Fig. 2). The variations of the solar activity, solar radius, and solar constant are expected to enter a grand minimum phase at the beginning of cycle 27 (tentatively in 2040). This phase can be from 45 to 65 years long. The heights of the peaks of cycles 25 and 26 will be determined more accurately when the solar constant or solar radius are measured in the minima of cycles 24 and 25 after the cycle maxima. Our predictions agree for the most part with the predictions from [1, 2, 7, 9, 10, 11] and disagree with the predictions from [6, 8].

Thus, we proposed a physically justified technique for the optimal prediction of the height of the next 11-year cycle prior to its beginning and the heights of several succeeding cycles. The method is based on (i) the fact that the long-term cyclic variations of the activity, radius, and solar constant are correlated in both phase and amplitude [1, 2], (ii) the dominant role of the global secular cycle in the development of the filial 11-year cycles of the solar activity, radius, and radiation flux [3], and (iii) the analysis of the secular variations of the solar radius or solar constant in the minima of three successive cycles. The difference of the solar radii or solar constants measured in the minima of two successive cycles was the physical parameter we used for the optimal prediction of the main characteristics of the next cycle, which will soon begin. We estimated its maximum activity level and the variations of the solar constant. The differences of the solar radii or solar constants measured in the minima of three successive cycles were used to forecast the development of the solar activity in several succeeding cycles. However, these predictions are less accurate.

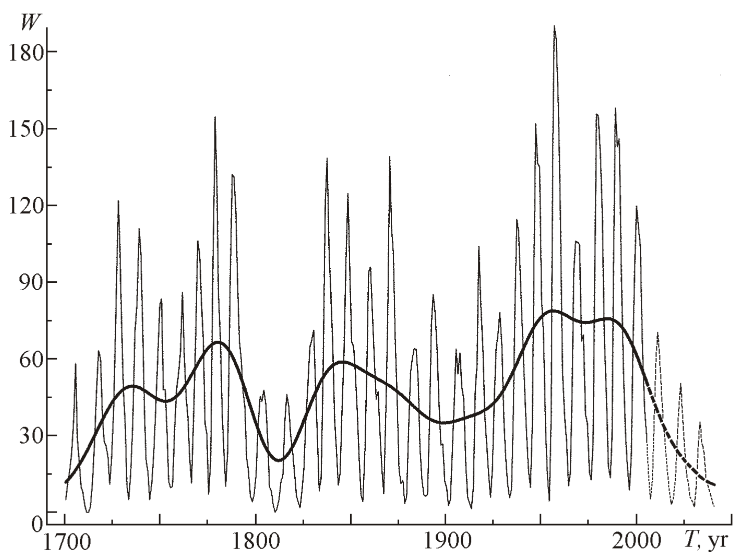

Fig. 2. (Solid curves) solar activity variations over the period from 1700 to 2006 (data from [1]) and (dashed curves) our predictions for the period from 2006 to 2040: (thin curve) 11-year variations, (thick curve) secular variations.

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